

A. Phillips, Jr.

Calculations of the Effect of Emitter Compensation on β and f_T of Bipolar Devices

Abstract: Significant increases in bipolar device β and f_T are predicted when emitter compensation is reduced. The prediction was made after accurately calculating all room temperature device parameters with a bipolar device program. The use of empirical concentration-dependent energy gap values allowed the accurate device calculation.

Introduction

The fact that bipolar device characteristics are influenced by the concentration-dependent band gap has been known for some time [1], but previous attempts to include the energy gap narrowing effects in our bipolar device programs did not render accurate results. The bipolar device programs are computer programs in which transistor parameters are calculated. The programs, based on the physics of the semiconductor, solve the transport equations, Poisson's equation, and the equations for electron and hole continuity, for a given device profile and bias condition.

A model was developed for including energy band gap narrowing effects in the bipolar device programs, which allowed, for the first time, accurate calculations of all measured room temperature device parameters of a modern high performance npn transistor. Calculations of β , f_T , and the dependence of collector current on base sheet resistance agreed with measurements when concentration-dependent energy band gap narrowing influences were included in a certain manner. Without the energy band gap narrowing model, none of these parameters could be accurately calculated with our bipolar device programs unless arbitrary assumptions were made about quantities such as carrier lifetimes.

Calculation procedures and results

Energy band gap narrowing is incorporated into bipolar device programs by replacing the intrinsic carrier concentration, n_i , with the carrier concentration of the doped material, n_{ie} , in the transport equations. The relation between n_i and n_{ie} is given by

$$n_{ie}^2 = n_i^2 \exp(\Delta E_g/kT)$$

where ΔE_g is the amount of energy band gap narrowing, k is the Boltzmann constant, and T is the absolute temperature. The equation implies that in the model the energy gap changes as a function of concentration, but the effective densities of states are unchanged. Concentration-dependent energy band gap narrowing is the difference between the intrinsic energy band gap and that for a specific donor and acceptor concentration at a given temperature. In the model, the energy band gap narrowing of donor atoms is added to that of acceptor atoms to obtain $\Delta E_g(N_d, N_a)$. This assumption is based on the idea that the impurity bands broaden about the energy of donor and acceptor levels in the energy gap for increasing impurity concentrations. The concentration-dependent energy band gap measurements of Vol'fson and Subashiev [2] were used for donor atoms and those of Slotboom and de Graaff [3] were used for acceptor atoms [4]. The energy gap was assumed to level off to its smallest measured value for dopant concentrations greater than the largest measured value [5]. Auger recombination, based on the concentration-dependent lifetime measurements of Beck and Conradt [6], in addition to the Hall, Shockley-Read recombination, was also included in the program. After successful calculations of all measured room temperature bipolar device characteristics, efforts were made to predict new effects in bipolar devices. One such effect was found. Device performance, β and f_T , was found to increase significantly when compensation was eliminated in the emitter [7].

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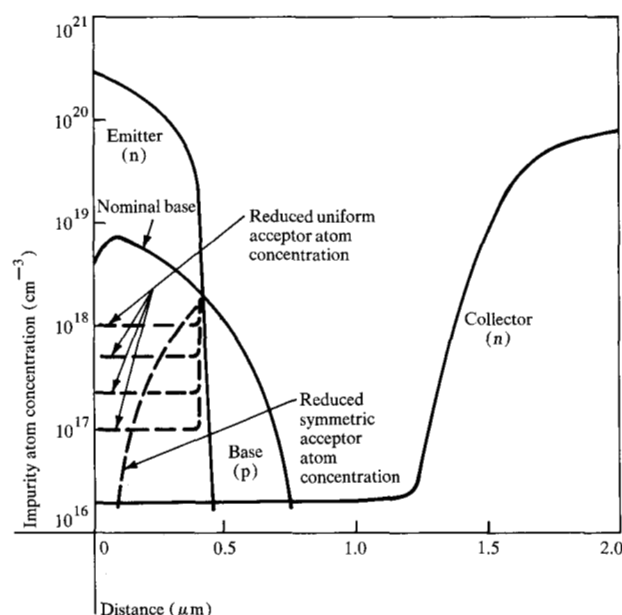


Figure 1 Impurity concentration as a function of distance for the npn transistor structures considered in this communication. The broken lines indicate the levels of emitter acceptor atom concentration.

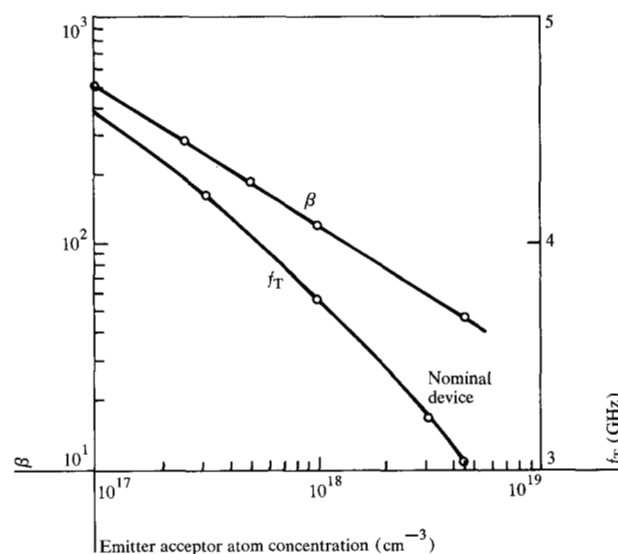


Figure 2 DC current gain, β , and f_T vs emitter acceptor atom concentration. Both β and f_T increase by reducing emitter compensation.

To illustrate this effect, consider an idealization in which the compensation in the emitter of a device similar to that of a modern high performance bipolar transistor is decreased in stages as shown in Fig. 1. In the reduced compensation profiles, the acceptor atoms in the emitter

are uniform from the surface to the region just before the depletion layer, after which they smoothly join the nominal base profile. The Gummel number, the emitter junction electric field, and the emitter and collector junction depths are unchanged for these profiles. Consequently, any changes in device performance are attributed to changes in compensation. These profiles may not be realizable in the laboratory with present methods of device fabrication. They are discussed in this communication to demonstrate simply and directly the influence of lowering the emitter compensation on bipolar device performance. Another base profile, which has a symmetric concentration profile on the emitter and base sides of the emitter junction, is also considered.

Figure 2 shows β as a function of the acceptor atom level in the emitter. Both β and f_T (also shown in Fig. 2) are determined by a one-dimensional bipolar device program developed by B. V. Gokhale [8] in which the transport equations are solved by numerical methods. For the nominal device shown in Fig. 1, β is 47. As the emitter acceptor level decreases, β increases. The calculation shows more than an order-of-magnitude increase in β to a value of 500 when the emitter acceptor atom concentration is reduced from the nominal device value to $1.0 \times 10^{17} \text{ cm}^{-3}$. The current gain has a value of 412 for the symmetrical base profile device. As the emitter acceptor concentration decreases, the energy band gap in the emitter widens, causing injected base current to decrease; thus, β increases. Electron current is constant since the emitter donor profile and the acceptor and donor profiles of the base region are unchanged in the calculations.

The curve of f_T as a function of emitter acceptor concentration increases monotonically in a manner similar to that of β as emitter acceptor concentration decreases. The calculations show, however, that the magnitude of the increase of f_T is not as great as that of β for reduced emitter compensation. Nominal device f_T is 3.03 GHz, and the symmetrical base device has a value of 4.0 GHz. H. H. Heimeier [9], by analyzing a simple bipolar structure with the energy band gap narrowing model, concluded that the increase in f_T is caused by the decrease in the level of minority carrier charge stored in the emitter with decreasing emitter compensation.

Conclusion

If devices are fabricated by putting less base dopant in the emitter of a bipolar transistor, as can be done with ion implantation techniques, the calculations in this communication show that both β and f_T will increase. Although all room temperature bipolar device parameters have been calculated accurately using the model, the contention here is not that these calculations of β and f_T are quantitatively accurate. The physics of real devices is more complicated than the physics included in our bipolar

program. The assertion in this communication is a qualitative one: the effect of reducing emitter compensation is to increase β and f_T .

Acknowledgments

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References and notes

1. W. L. Kauffman and A. A. Bergh, *IEEE Trans. Electron Devices* **ED-15**, 732 (1968).
2. A. A. Vol'fson and V. K. Subashiev, *Soviet Physics Semiconductors* **1**, 327 (1967).
3. J. W. Slotboom and H. C. de Graaff, *Solid State Electron.* **19**, 857 (1976).
4. Vol'fson and Subashiev's measurements were made for n- and p-type silicon using optical excitation techniques. Slotboom and de Graaff employed an npn bipolar device for measurements made on uniformly doped p material. Measurements of the band gap in p material using these techniques are different. Since there were no bipolar device measurements for n-type material, the data of Vol'fson and Subashiev were used. The discrepancy in the results of the measurements using these two techniques implies that the calculations may be fortuitous. Clearly, there is a need for both more experimental and theoretical study of heavily doped and compensated material.
5. Other assumptions made about the energy gap for concentrations higher than the largest measured value resulted in less accurate calculations of bipolar device parameters. It was hypothesized, for example, that the slope of the energy gap in the unmeasured concentration range was the same as that at the largest measured concentration.
6. J. D. Beck and R. Conradt, *Solid State Commun.* **13**, 93 (1973).
7. W. Dumke has informed me in a private communication that his recent measurements made on diodes at 77 degrees K indicate that β increases as emitter compensation is reduced. His limited measurements did not show that β increases as much as these calculations indicate.
8. B. V. Gokhale, *IEEE Trans. Electron Devices* **ED-17**, 594 (1970).
9. H. H. Heimeier, private communication.

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The author is located at the IBM Data Systems Division laboratory, East Fishkill (Hopewell Junction), New York 12533.